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## SCIENCE & TECHNOLOGY:



# NBS/RIA ROBOTICS RESEARCH WORKSHOP

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# COMPUTER SCIENCE & TECHNOLOGY:

## NBS/RIA Robotics Research Workshop

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Proceedings of the NBS/RIA Workshop on  
Robotic Research Held at Williamsburg, Virginia

July 12-13, 1977

Edited by

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Anthony J. Barbera

Institute for Computer Sciences and Technology  
National Bureau of Standards  
Washington, D.C. 20234

Sponsored by the

National Bureau of Standards

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Robot Institute of America



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## ABSTRACT

The NBS/RIA Robotics Research Workshop had two objectives: (1) to provide a forum for structured discussions between researchers in robotics and manufacturers and users of robot systems; and (2) to develop a consensus forecast of future developments in sensors and control systems for industrial robots.

The two day Workshop brought together 31 researchers, manufacturers, and users of industrial robots in order to determine the needs and priorities for future research in sensors and control techniques for industrial robots. There were no formal papers; instead, small group discussions and presentations and the preparation of a Delphi Forecast were used to address research needs and priorities.

**Key Words:** Control systems; Delphi Forecast; industrial robots; robot applications; robotics research; sensors.

## I. INTRODUCTION

On July 12 and 13, 1977, a Workshop on Robotics Research was held at the Williamsburg Lodge in Williamsburg, Virginia. The Workshop, which was arranged by the National Bureau of Standards in cooperation with the Robot Institute of America, had two objectives:

- . To provide a forum for structured discussions between researchers in robotics and manufacturers and users of robot systems; and
- . To develop a consensus forecast of future developments in sensors and control systems for industrial robots.

The two day Workshop brought together 31 researchers, manufacturers, and users of industrial robots in order to determine the needs and priorities for future research in sensors and control techniques for industrial robots. There were no formal papers; instead, small group discussions and presentations and the preparation of a Delphi Forecast were used to address research needs and priorities.

A list of attendees is given in Table 1.

Attendees were split into six small groups: researchers, manufacturers, and the four application areas of welding, aerospace, assembly, and machine loading. The results of these small group discussions are presented in Part II of this Proceedings.

A Delphi Forecast on needs and priorities for sensor and computer control technologies was carried out by the participants. The first round was prepared prior to the Workshop, analyzed during the first day, and returned to the participants the first evening. The results of the first round were discussed on the second day, and a second round was turned in at the end of the meeting. The results of the second round are presented in Part III of this Proceedings.

Key conclusions that can be drawn from the Delphi Forecast are:

- . Sensor controlled movements of robots appear to be a highly desirable feature in the implementation of robots in present and future applications. The most desirable sensory capabilities are simple vision in welding and aerospace laminate handling applications and touch in assembly, machine tool, and press and casting operations.
- . The robot users feel that a cost of \$7000 can be justified for simple vision and \$2000 for touch sensing.
- . There was a strong consensus among all participants that simple vision is the number one priority for research and development efforts.
- . All sensory capabilities, including complex vision, are seen to reach commercial availability before 1985.
- . The data supplied here indicates that for almost all applications, the work-piece position and orientation are already known to within plus or minus 1" and plus or minus 20 degrees. This type of imprecision in the known location of the workpiece should be easily accommodated for by simple vision.
- . A shift was seen into the middle and late 1980's away from the simple bang-bang, and point-to-point servo control systems to more sophisticated computer control that would perform coordinate transformations and sensory feedback control.
- . By 1985, it was felt that 10% of the robots would be incorporated in integrated computer aided manufacturing systems.

- . The market for industrial robots in 1985 is predicted to be approximately \$200 million, with a growth rate of 25% per year during the 1980's.

TABLE I  
ADDRESS LIST OF WORKSHOP PARTICIPANTS

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## II. DISCUSSION GROUPS

The participants were assigned to six groups on the basis of their expertise in a particular area. Four of these groups encompassed the major application areas of robots, both at the present time and in the near future. These four application areas were welding, aerospace, assembly and machine loading. The fifth group consisted of a number of researchers in the area of robotics, and the sixth group was made up of representatives from the robot manufacturers.

Each of these discussion groups met separately at the beginning of the workshop. They directed their efforts to identifying and quantifying as much as possible their particular requirements for control system capabilities and sensory feedback. After these individual meetings occurred, all of the participants were assembled together. A spokesman for each group presented a summary of the consensus view of his group's particular needs. This allowed the user groups to communicate their needs to both the researchers and robot manufacturers while emphasizing the economic restrictions present in the manufacturing environment. The researchers were able to correlate their work to present and future applications, while the robot manufacturers offered insight into the problems of implementing research ideas into reliable, economical products to provide to the user group.

Each of these groups prepared a written summary that is reprinted here.

### 1. WELDING

#### A. INTRODUCTION

This application area was concerned with both spot and arc welding.

Spot welding is a typical fastening operation for pieces of sheet metal such as the parts of automobile bodies. This particular application presently employs a large percentage of industrial robots. The workpieces on the automobile respot lines consist of car bodies and/or their subassemblies that have had a sufficient number of welds applied to hold the pieces together. Robots carrying spot welding guns fill in the remaining welds. In order for the robots to correctly place these welds, the workpieces have to be accurately positioned by indexed lines, jigs or clamps. No sensory capability is presently available to allow the robot to locate and correct for a slightly misaligned part.

Arc welding operations are typified by the fusion joining of large pieces of steel plate. Problems arise because of non uniformity of gap size at the junction of two work pieces introduced by the cutting process. A human worker will lay down a smaller or larger weld bead or a number of beads to accommodate this variation. An additional problem is created by warping of the plates due to heating during the welding process. This causes the junction to move in space as the welding operation proceeds which can result in displacements of inches when plates tens of feet long are being joined.

#### B. GROUP MEMBERS

Tom Blunt - Ford Motor Company  
Taft Christian - Deere & Company  
Dan Reinhart - Caterpillar Tractor

#### C. GROUP REPORT

The following is a summary report provided by Tom Blunt from the Ford Motor Company.

Representatives from Ford, Deere, and Caterpillar discussed the current state-of-the-art technology as relates to the welding process. Deere and

Caterpillar do the majority of their welding with the fusion process and Ford with spot resistance, however the basics of both processes present similar problems.

Virtually all manufacturing processes seem to break down into four main categories relevant to robot capabilities.

Category 1 - Stationary Operations - Fixtured  
Category 2 - Stationary Operations - Non-fixtured  
Category 3 - Moving Operations - Fixtured  
Category 4 - Moving Operations - Non-fixtured

The consensus was that operations in Category 1 can be done by all "smart" machines and a significant number of limited sequence machines. Several machines on the market can do Category 3 operations, and we all agreed that the robot manufacturers should focus their attention, on machines in these categories, toward increased reliability and cost reduction.

Non-fixtured operations, Categories 2 and 4, present unique problems and hence requirements for machine invention. Most non-fixtured operations, stationary or moving, present to the robot a work piece which is randomly located within narrow limits i.e., the front is always to the front, top always up, etc. This misalignment can be described as approximately within plus or minus 1" of a known nominal position. This slight positional error requires a device which can compensate or shift a pretaught program to the new "sensed" location or control a "smart tool" in one or more axes.

It appears that due to size, environmental requirements and durability characteristics the technology which seems to offer the most promise at the present time is simple vision in the form of edge finding. The essential requirement is that the sensing devices be non-contact.

#### D. ADDITIONAL DISCUSSION

During the presentation to the workshop, additional emphasis was placed on the requirement that the sensors be non-contacting for the spot welding applications. Specifically, Ford's experience with contact types of sensors was that they presented a lot of durability, maintenance and lifetime problems. Therefore, a non-contact type of sensor was favored.

It was also suggested that since the objective is to position the tool to the workpiece that some thought might be given to "smart" tools as opposed to "smart" robots. The robot would position this tool to the same spot each time while the tool itself would have one or more servoed axes under sensor control to correct for misalignments of the part.

Presently, for automotive spot welding operations, the cost of the robot approximates \$60,000 to \$65,000 with an additional \$20,000 to \$25,000 being required for the extra facilities and hard tooling required to put the workpiece into a known position. This expenditure for extra tooling provides a ball park figure for the cost that could be justified for the sensors and control for the robot or a "smart" tool.

Additional comments were made concerning the hostile environment of welding - weld flash, smoke, oil, electromagnetic noise, heat etc. and the requirements this environment will place on sensors if they are to be reliable.

## 2. AEROSPACE

### A. INTRODUCTION

The aerospace industry, while not presently a major user of industrial robots, is seriously looking into possible labor intensive operations that might be automated. Preliminary studies along this line by the different aero-space manufacturers and the Air Force have identified several potential application areas. These are described in the GROUP REPORT.

### B. GROUP MEMBERS

Jerry Ennis - McDonnell Douglas Corporation

Bob Forrer - Northrop Corporation

Riley Kuehn - The Boeing Company

Dan Shunk - ICAM Program, USAF

### C. GROUP REPORT

The following is a summary report provided by Dan Shunk from the ICAM Program, USAF.

The subcommittee was charged with attempting to identify the sensor and control requirements for aerospace with regard to robotic applications.

It should be stressed at the outset that the comments expressed herein are in the comments of individuals and should not be construed as being a consensus from the entire aerospace community. It can be assumed that many requirements stated are consistent throughout aerospace; however, every aerospace company is different and may have varying requirements for sensors and controls due to their individual applications.

The subcommittee broke the aerospace category into three areas of application consistent with the Delphi forecast breakdown. These three areas are:

- i) Aerospace Laminate Handling
- ii) Aerospace Drilling, Routing and Fastening
- iii) Small Part Assembly

All other areas of the Delphi questionnaire are of interest to aerospace but time did not permit discussion in these areas.

#### Aerospace Laminate Handling

This should more appropriately be called "Composite Handling and Layup." Considering the systems approach, the handling and layup are key elements of an integrated composites cell. Using either rolls of composite material or broad-goods, several key, high level robotic sensors and controls are necessary. These are outlined here.

- i) Hierarchic controls for the complex computer controls necessary for selection of cut parts and/or layup of parts are very necessary.
- ii) Due to the complex tooling and accuracy constraints in layups, tight tolerances must be maintained. Here sensors (possibly vision) may be able to give some relief.
- iii) Sensors are also needed for part handling that can discriminate "black-on-black" for ply layups.
- iv) Off-line programming would be a tremendous aid in allowing data base definition of layup requirements that could be used in an effective, easy manner.

## Aerospace Drilling, Routing and Fastening

Due to the arrangement within the aerospace shops, routing is considered a fabrication operation whereas drilling and fastening are considered assembly operations. Again the systems approach is emphasized. Currently tremendous costs are incurred due to tooling requirements. If an off-line programming language could be developed that could tie the design data base to the routers without having to use expensive tooling, significant cost savings are attainable. Also sensor requirements to hold tolerances without fixed, expensive tooling would also benefit. Here, a Group Technology approach is necessary to gain economies of scale in the flexible tooling design.

With regard to drilling and fastening, little was discussed.

### Small Part Assembly

Many aerospace small sheet metal assemblies can be assembled with the aid of robotics if some basic requirements can be developed. Identified as necessary for this application is an off-line programming language that can draw upon the parametric data of the design data base and then can be used to develop procedures for the small part assemblies.

### Summary

The aerospace representatives wish to stress the need for systems approaches that incorporate robots. Use of existing data bases, the Group Technology philosophy, cellular manufacturing concepts and flexible tooling must be considered. It should be mentioned that at times the amortization of the tooling may be greater than the part fabrication cost. For this reason, the flexibility of the robot should be used to its greatest advantage.

A summary of requirements for sensors and controls should be:

- i) greater accuracy in the robots
- ii) off-line programming
- iii) advanced tooling concepts incorporating robots
- iv) vision type sensors for selections.

### 3. ASSEMBLY

#### A. INTRODUCTION

This application area has been and probably will continue to be an exceedingly difficult one for robots. Assembly is a very complex operation that humans accomplish while making use of very sophisticated sensory processing, decision making, problem solving, coordinate offsets and transformations, compliance, and high speed manual dexterity. This problem has been studied in great depth at a number of research institutions and at a number of manufacturers' research laboratories. It is still, however, more of a research area than an applications area.

The only presently known robot assembly work being done in a manufacturing environment is at Olivetti in Italy. There, overhead rail, N/C like tool handling robots are being used to assemble typewriters and insert IC chips into printed circuit boards. These computer controlled robots are equipped with touch and force sensors that allow the robot to partially cope with uncertainties in the environment and to do error branching procedures.

A number of manufacturers in this country are looking into the possible use of robots in some of their assembly operations. It was decided to place representatives from these manufacturers' research laboratories into this assembly group.

#### B. GROUP MEMBERS

Dick Beecher - General Motors  
Harry Richter - IBM  
Gordon Robertson - Western Electric  
Bob Stewart - Westinghouse

#### C. GROUP REPORT

The following is a summary report provided by Gordon Robertson from Western Electric.

All members of the assembly group were in basic agreement on requirements with slight differences on emphasis. We started out by considering the philosophy behind the choice of sensors. Three of the four representatives felt that some form of vision was important to the success of an assembly robot, and everyone agreed that a robot suitable for assembly is not yet commercially available.

Specifically, one representative performed assembly by lightly structuring the environment. Considerable effort has been expended in the past to make a uniform set of parts to be assembled, so it was feasible to use feeders and other positioning devices to enable a robot to acquire a part by dead reckoning. The other three representatives were of the opinion that an orienting feeder for most parts was impractical in terms of size and cost, so a more realistic approach was to use simple non-orienting dispensers coupled with vision.

There were few differences in the requirements for vision. A binary image with 100 x 100 resolution was considered adequate, with the option of including a grey scale converter at a later time. The time to recognize an object and to determine its orientation should be less than two seconds, which would be concurrent with some other activity of the robot arm.

IBM felt that 10% - 20% of its assembly required vision, and the other three representatives thought that a better figure for them was 50%.

Regarding the arm and control strategy, it was agreed that to some extent the assembly line could be engineered to meet the robot capability, but Western Electric felt that it would be difficult to make a robot assembly station acceptable if much re-engineering was involved. The number of axes an arm should have was briefly considered, and five axes with an optional add-on sixth was regarded as adequate. IBM favored the modular expandable concept.

D. ADDITIONAL DISCUSSION

There was a general consensus that the present state of the art in touch, proximity, and simple force sensors was sufficient for assembly operations. Complex force, however, was considered still to be a research area. MIT's work with a remote center compliant device has demonstrated how, in some applications, processing of complex force information can be designed into a passive mechanical system.

Bin picking of parts for assembly was judged to be uneconomical at the present time.

A general comment expressed during the presentation was that a large part of the problem in using robots for assembly operations was rooted in the fact that parts have been designed for assembly by people, not by automated equipment. It was felt the basic redesign of products with robot assembly in mind would go far in making this a viable and economical technique.

## 4. MACHINE LOADING

### A. INTRODUCTION

This area was originally classified as machine loading/unloading. However, it soon became apparent that, in about all cases, the unloading of a workpiece from a machine is a far simpler problem than the loading. Unloading parts from machines is a straight forward task that can be accomplished by present commercial robots. The machine determines the location of the part to a sufficient positional accuracy and orientation for grasping by the robot. Therefore, the unloading problem was discussed as essentially solved with present technology (with the exception of parts in metal cutting machines that produce long, tangling stringers of waste metal).

The group directed its discussion to the problems of acquiring the workpieces to be loaded into the machines. These pieces typically arrive at work stations on pallets, in bins, and on conveyors with varying degrees of uncertainty in position and orientation.

### B. GROUP MEMBERS

Keith Dowler - Los Alamos  
Kurt Landsberg - AL OA  
Tony Barbera - NBS

### C. GROUP REPORT

The following is a summary report provided by Kurt Landsberg from ALCOA.

It should be noted that there are many applications within machine tool loading and unloading and press loading and unloading that can be accomplished with today's technology. The purpose of the group discussion was not to look at those types of problems, but rather to look for what was needed in the future.

The group saw a very strong need for having simple vision. Simple vision, rather than complex vision, is desirable because part identity is known and recognition of an edge, a circle, holes, corners, etc. will allow us to find the location of the part, orient the part, and load it into the appropriate machine tool or press. There are many applications where part positioning is within plus or minus 1". However, the ability to go to plus or minus 3" would be desirable.

Proximity sensors would also be very desirable in loading machine tools and presses. These sensors could be used to detect presence or absence of a part without contact. It would also be valuable in determining the location of a part through measurement techniques.

Quick programming of robots is very essential in job shop type application. With many of the systems on the market today, programs can be stored on magnetic cassettes. This is a very helpful feature. However, in many applications, dies are not put in the exact same location in the press every time. Having to touch up the program every time you run a particular part is not desirable. Thus, we would like to incorporate the ability of the robot to learn, after it has been taught the basic program. In the example of a die being mislocated in a press, the robot would go and find the die via simple force sensors. It would learn the new position and go to it as required. The group classified this as the ability for a robot to learn and not simply be taught through pendant control.

When all the groups reconvened for discussions of the Delphi forecast, it became apparent another point should be included as it pertains to machine

tool and press loading and unloading. Press loading is much more difficult than press unloading. When unloading the press, you know precisely where the part is. This is not the case when loading a press. The comments of the group were basically directed to the more difficult task of loading presses and loading machine tools. Machine tool unloading has one basic problem; the removal of metal chips. I do not believe this is a task that can be addressed by either the National Bureau of Standards or Robot Manufacturers, but rather one that can be examined by researchers and users.

The group did not address itself to the classic bin picking and orienting problem. However, since the Workshop I have become aware of these types of problems within Alcoa. As mentioned at the Workshop, it is a classic problem for virtually all machine tool operations. To be cost effective, bin picking must be done rapidly. The problems that have been observed to this point in time are: (1) no one has effectively solved the problem and (2) the solution may be costly and too time consuming. However, solving the problem will permit the automation of tasks presently presumed to be impossible. A personal (not the group) opinion is that this would be worth \$10,000 to \$15,000 as an add on package to a robot automation system.

#### D. ADDITIONAL DISCUSSION

Additional discussion on the use of a simple vision system (a system that can detect edges, corners, holes, etc.) to cause the robot to properly acquire parts from moving conveyors led to a time constraint of 1 second or less to determine part location and orientation.

As mentioned in the group report, the problem of bin picking is believed to require complex vision which is not available in the near future at an acceptable cost. However, it was suggested that a partial solution to the bin picking problem may be realized by transferring the parts onto a flat surface. Since for most parts there are a limited number of stable states on a plane, a simple vision system might be used to determine which of these states and what orientation the object is in. The robot could then be directed to grasp it correctly.

There was some general discussion and agreement that part of the loading problem is the failure to maintain workpiece orientation. Every time a workpiece is in a tool, its position and orientation are accurately known. However, most facilities continually throw away this information by dumping the workpieces in bins or on conveyors. Bins and conveyors have been used as cheap buffer areas to allow for a lack of control in pacing the various machine operations. This has been a reasonable method in the past, since it is a simple task for a man to reorient the parts from these buffer areas while he is loading it in the next machine. However, for robots to be successfully used in machine tool loading, entire system design should be considered, including keeping the part orientation once it has been acquired.

There was a general consensus that new machine tool facilities are still being designed around people instead of automated equipment, thereby making it much more difficult to justify the installation of a robot because of the additional costs involved in tailoring the workstation to the robot.

## 5. RESEARCHERS

### A. INTRODUCTION

Members of a number of research institutions were present and presented summaries of their institutions' efforts in the areas of sensors and computer control.

### B. GROUP MEMBERS

Jim Albus - National Bureau of Standards  
John Birk - University of Rhode Island  
Jim Nevins - M.I.T.  
Charles Rosen - Stanford Research Institute  
Delbert Tesar - University of Florida  
Michael Wesley - IBM

### C. GROUP REPORT

The following is a summary report provided by Jim Albus from the National Bureau of Standards.

#### Charles Stark Draper Labs

James Nevins presented a short overview of the C. S. Draper program. He described the early work in part mating studies using force feedback to overcome or avoid "jamming" or "wedging." Detailed in depth analytical studies were made of the sources of alignment errors which cause parts to jam. Parts were classified according to their size and geometric characteristics and descriptions of the force-friction events during the mating process including the determination of ratios between the applied forces and moments to avoid jamming during mating. These analytical studies were verified by experimental tests.

One of the results of these studies was the discovery that passive compliance of the proper kind would greatly increase the range of errors which could be tolerated before jamming occurred. This led to the development of the Remote Center Compliance (RCC) device which produces a lateral translation motion in response to a lateral force at the tip of the object being inserted. Experiments with this device have demonstrated successful assembly of objects with large initial errors. These tasks were previously difficult or impossible except with special fixtures or guides. Insertion of bearings 1.6" in diameter into holes with .0007" clearance has been routinely accomplished in .2 seconds. The RCC device thus provides the function of nulling off-axis forces and torques in a simpler, more reliable, and less expensive way than sensory feedback can.

The Draper lab has also quantified many of the economic constraints and driving forces involved in robot assembly system configuration. Many industrial products were studied to determine the statistics of the required assembly tasks. Single insertions were the most common tasks, followed by screw insertion, and insertion with a twist for seating gears or keyways. Also common were multiple insertions or alignments, press fits, and insertion with spring loaded retainers. Other tasks were much less common.

Cost trade offs involving speed of operation and capital costs have also been studied. These cost sensitivity analyses tend to favor minimum configuration systems.

#### Stanford Research Institute

Dr. Charles Rosen presented an overview of the SRI program in simple vision systems and parts acquisition and handling systems. He described the type of capabilities which can be achieved with a low resolution (128x128) solid

state camera and a microcomputer of the LSI-11 class. He observed that, while proximity sensing by optical, electrical, magnetic, eddy-current means can be often used in specialized tasks, electro-optical sensing employing television-type transducers (visual sensing) offers a more general approach to a wide range of problems. In particular, the solid-state camera (linear diode array or two-dimensional arrays) can readily generate an image which is far richer in information content than other noncontact sensors. Cameras and associated microcomputers are now at hand at acceptable cost, and relatively simple software has been developed to deal effectively with several large classes of useful sensing. These applications all fall under the classification of "simple" vision, which includes detection and use of edges, holes, corners and other features, shape discrimination. It is true that a relatively inexpensive vision system (in equipment and computer program complexity) can at present only accommodate binary images with modest resolution (100-200 pixels in a line). It is equally true that we can anticipate rapid progress in the next five years in the development and implementation of advanced systems which require higher resolution, grey-scale processing or the equivalent, and also the use of other sensory techniques which extract depth or range information, so that complex visual sensing or scene analysis will become a practical reality.

Simple vision principles and reduction to practice have been demonstrated in a few laboratories in the U.S. and Japan. In particular, SRI has demonstrated a relatively simple system which can effect the recognition and determination of position and orientation of workpieces which are viewed one at a time on fixed and moving conveyors. This capability has been applied to material-handling, parts presentation, bin-picking and visual servoing applications. SRI intends to pursue these developments vigorously in its present programs, and is aware of proprietary work of this kind at several large industrial laboratories. These techniques are at the stage in which one cannot, as yet, purchase a complete off-the-shelf system, but one must assemble available components and engineer hardware and software specifically for each new task. SRI hopes to develop a visual module (hardware and software) which would greatly simplify the required application engineering.

The same general principles and apparatus of visual sensing can be applied to inspection, another function essential for advanced automation. Simple or gross inspection which is qualitative and semi-quantitative has been demonstrated at SRI and elsewhere using simple vision programs and equipment. Defective or wrong parts can be recognized and automatically discarded. Within the limits of available resolution and grey-scale processing, many inspection tasks performed by humans, with no measuring tools, using the equivalent of one eye alone, can be implemented today at acceptable speed and cost. This is an enormously fertile field for future research and development and may be even more important, in an economic sense, than all the other visual sensing problems which we have addressed.

In summary, simple vision is available today at the advanced development stage, ready for application to large classes of factory operations. Dr. Rosen predicts that by 1982 advanced simple vision and more complex vision techniques will be universally applicable to most of the major automation areas.

#### IBM

Dr. Michael Wesley described the IBM automation research program in six areas.

1. Geometric modeling of part descriptions which can serve as a data base for computer aided design systems, APT part and machine tool control programming, and robot programming.

2. High level languages which can be used to provide efficient man-machine communication at all levels of computer aided design and manufacturing systems.
3. Vision systems for part identification and acquisition, particularly with regards to small parts assembly tasks.
4. Distributed processing techniques and systems based on large scale integrated (LSI) circuit technology for use in high performance sensory-interactive motor-control systems.
5. Sensor design for touch, force, and high speed visual analysis.
6. Error detection and recovery techniques for enhanced safety and system reliability.

#### University of Florida

Professor Delbert Tesar described research efforts at the University of Florida which are directed at obtaining a more fundamental understanding of optimum structures for large distributed control systems. He pointed out that such systems will involve many levels of nested feedback loops as well as sophisticated feedforward predictive capabilities.

Dr. Tesar mentioned that the University of Florida would host a workshop in November 1977 addressing the issues of geometry, modeling, control, medical applications, and automation in the design of manipulator and teleoperator systems.

The requirements related to medical applications were also discussed. In particular the need for flexible, efficient prosthetic manipulators was stressed and various surgical procedures requiring specialized micromanipulators were discussed.

The following is a list of the principle research objectives of the University of Florida program:

1. Classification
  - \*A. Full range of R, P devices
  - B. Structural description
  - C. Motion potential and range studies
  - D. Sub- and extra-modal capability
  - E. Trends for redesign
  - \*F. Energy industry requirements
2. Geometry
  - A. Computation base
  - \*B. Quartic level devices
  - C. General system including 6R
  - \*D. Hand coordinate specification
  - \*E. Compendium on manipulator geometry
3. Dynamic Studies
  - A. Model
  - B. Secondary functions
  - C. Deformation phenomena in actuators
  - D. Actuator requirements
  - E. Kineto-elastodynamic considerations

4. Experimental Evaluation
  - A. Digital coupling of MBA arm
  - \*B. Digital interface and microprocessors
  - C. Develop computer hardware
  - D. Industrial test activity
  - E. Role of joystick
5. Control Concepts
  - A. Role of feedback
  - B. Obstacle avoidance
  - C. Criteria for optimum operation
  - D. Selection of motion pathways
  - E. Hierarchical control studies
  - F. Role of sensors

\*Items already underway.

#### University of Rhode Island

Professor John Birk described research work at the University of Rhode Island which is primarily directed at the problem of bin-picking, i.e. the acquisition of randomly oriented parts from a bin containing many such parts.

Four techniques exist to handle unoriented workpieces: human labor, mechanical feeders, preserving orientation, and using mechanical separators. Research at the University of Rhode Island is concerned with using vision to enable robots to acquire pieces directly from bins. This ability will offer a fifth alternative to the problem of handling unoriented parts. It is worthwhile to develop because significant disadvantages exist to the other approaches. Lists of disadvantages are compiled in the third URI research report which will be completed in August. Naturally, the approach being developed will have to compete with the other methods on an economic basis.

The difficulties of the bin picking problem were briefly mentioned. These difficulties include the fact that there are six degrees of uncertainty of a piece in a bin, three of position and three of orientation. Another problem is that a method is needed for relating image features to workpiece orientation and position. Another problem is that a strategy and a means to acquire workpieces must be developed so that acquired pieces can be transported to their goal. Another problem is to determine the orientation of a workpiece in the hand, since uncertainty in orientation may be introduced during acquisition.

Currently experiments are in progress on subproblems of the bin picking problem. By August 1978, it is planned to have an integrated experimental bin picking robot system functioning (to some extent). At that time, it seems appropriate to get serious about technology transfer to industry. A seminar is planned for mid-August 1978 to explain in detail the technology which has been developed and to explore technology transfer opportunities. It was predicted that during the next 5 years, continued research would improve the performance of the system in terms of speed, workpiece variety, etc., so that in 5 years the approach of directly feeding from bins would become economically competitive for a number of industrial applications.

An inquiry was made about the new technique that would enable the bin picking problem to be solved. The method of solution lies primarily in organizing the problem. This means that sufficient time must be spent on identifying what the subproblems are and what options exist to solve them. It was also mentioned that we could look forward to better computer hardware in five years and that some time consuming image processing needs could benefit from special electronic hardware designs to extract features.

## National Bureau of Standards

Dr. James Albus outlined NBS research work in three areas:

1. Definition of a logical structure and notation for dealing with distributed sensory-interactive control systems.
2. Design of a programming language for implementing sensory-interactive robot control.
3. Investigation of a new type of computational device called CMAC (Cerebellar Model Arithmetic Computer) for multivariate adaptive control tasks.

The NBS concept is to define any complex control problem as a hierarchy of and/or task decompositions. For example a task such as ASSEMBLE AB can be broken into a sequence of subtasks, FETCH A, FETCH B, MATE A to B, FASTEN A to B etc.. Each of these subtasks can itself be decomposed into a sequence of elemental moves such as REACH TO A, CENTER OVER PART, GRASP, MOVE TO C, RELEASE, etc. These elemental moves can be further decomposed into trajectory segments in work space which are transformed into commands in joint angle space, and finally into sequences of voltage signals to valves and actuators. At each level of the hierarchy, feedback may interact with the task decomposition operator such that the system reacts in real-time to uncertainties and perturbations in the environment.

The advantage of structuring the control problem in this way is that it makes the control system modular. Each decomposition can be implemented as a self contained subroutine or even as a separate piece of hardware in a microprocessor implementation.

## 6. ROBOT MANUFACTURERS

### A. INTRODUCTION

This group is the interface between the researchers and the potential robot users. They have to provide the machines to do everything the users desire, while incorporating the sophisticated techniques from the research groups at an economical cost with very high reliability under hostile environmental conditions. This is no easy task.

### B. GROUP MEMBERS

Joseph Engelberger - Unimation  
John Farentine - General Electric  
Brian Ford - ASEA  
Dick Hohn - Cincinnati Milacron  
Jerry Kirsch - Autoplace  
Harry Loh - AMF Versatran  
Jack Stroman - Bendix  
Don Vincent - SME/RIA  
Walt Weisel - Prab

### C. GROUP REPORT

The following is a summary report provided by Don Vincent from the Robot Institute of America.

#### Discussion Guidelines

The Group agreed that the application areas listed on the Delphi Forecast Questionnaire, provided by NBS, would be used as points of discussion by the manufacturers. Specific activities discussed were: Spot Welding; Arc Welding; Aerospace (laminate handling, drilling, routing, fastening); Machine Tool Loading/Unloading; Small Parts Assembly. Each activity was discussed so as to provide direction for robot manufacturers . . . advise for users . . . challenges for researchers.

#### Spot Welding

Discussion centered on the needs of manufacturers, users, and researchers in spot welding applications. Basically, if the robot knows where the work is, it can weld. At the present time, a great deal of money is being spent in orientation. The manufacturers realize that users want welding applications to be accomplished during movement of the body.

Manufacturers -- need to build the robots reliability and cope with motion and sensory feedback. There is no need for touch, force or complex vision in spot welding.

Users -- get the work into place to about one inch. Fixture the line and do something with the guidance system.

Researchers -- provide proximity type of vision (not necessarily optical).

#### Arc Welding

Manufacturers and Researchers -- work together to provide reasonable complex vision feedback to sense the character of the joint just in front of the bead. Need "positional information." This must be done with little space intrusion by the "eye." There is no need for touch or force sensing.

Users -- make accurate parts and jigs so that straight forward path control will produce a good weld.

### Aerospace

The discussion of robot applications in the aerospace industry revealed that more information is needed about the economics of using robots in aerospace. The manufacturers would like to see more justification for robot usage in the industry and felt users should do a better job of defining the problem. At this time, the aerospace industry does not have a good robot application in its manufacturing activities. Future robot development for aerospace applications will require a higher level language (off-line programming) and large capital expenditures by aerospace companies.

### Machine Loading/Unloading

In discussing limited sequence robots being applied to machine tool loading/unloading, it was agreed that this entire operation needs to be better automated, with specified automatic clamping and machine cycling, automated chucks that could handle a wide variety of part sizes, automatic chip breaking and chip removal.

Users -- plant layout should be in the interest of robotics for robot integration with totally automated manufacturing systems. Machine location should allow robot time sharing.

Researchers -- concentrate on bin picking of parts for a bank of machine tools. This requires complex vision.

### Small Parts Assembly

With the present robot technology, it is difficult to compete with a human in small parts assembly. In the 2-5 year time frame the technology may advance to cost effectively accomplish small parts assembly with robotics. The key to robots performing parts assembly is in the orientation of the part, (bin picking). It is a requirement that the part comes to the robot oriented and ready for assembly.



### III. DELPHI FORECAST

#### A. INTRODUCTION

A list of 10 questions relating to sensors, control system capabilities and market predictions was distributed to the participants before the workshop.

The first round of the Delphi procedure consisted of tabulating this original set of responses, discussing them at the workshop, and then allowing all of the participants to respond again to the questionnaire. It was hoped by this method that a consensus could be reached in this second set of responses. The results of this second round are printed here.

For most answers, the results are in the form of three numbers. The first number is the arithmetic mean of all of the responses. The next two numbers are the cut off values for the upper and lower quartiles. As an example, consider the responses to a question involving the prediction of the year for some event. The results might be summarized as follows:

1985  
1984-1987

Here, the mean value of all of the responses is the year 1985. The middle 50% of the responses fell between the year 1984 and 1987 while 25% of the responses were less than 1984 and 25% were greater than 1987.

This questionnaire covered a large range of application areas. The respondents were advised to fill in only that part of the questionnaire that concerned the area(s) with which they were most familiar.

#### B. SENSORS

##### Question 1a)

This question was concerned with the importance of different types of sensors in terms of their immediate economic benefit for the user. This takes into consideration the cost for the sensor in relation to the relative increase in capability it might give a particular application. For an example, consider spot welding of automobile bodies. The addition of simple vision could allow the robot to accurately place the welds on cars carried by existing transfer lines. This would eliminate the need of the additional expensive indexing and positioning equipment that presently has to be installed for robots to perform this task. Thus, this sensory capability received a priority ranking of one for the spot welding application because of the large economic benefit it would provide if available.

For this question, the results are expressed as a priority number along with, in parentheses, the arithmetic mean of the responses. Thus, each application area will have a priority ranking (from one to six) of the different sensors. This is merely an ordering according to the average values of the responses. In some cases, the average values reflect a real priority ranking. In other cases, however, the average values are very close together, and therefore, the difference in priority ranking becomes less significant.

For an example, in the injection/casting unloading area, simple force was ranked #2 and proximity #3. Their average values, however, were 2.4 and 2.6, respectively. Thus, the above priority ranking is less significant and both simple force and proximity could be considered almost equivalent in importance.

During the discussion period, the sensory capability of touch was enlarged upon. It was redefined to include any contacting sensor that provides a signal that is proportional to the displacement of that sensor as well as the simple on-off switch.

Response to 1a)

- 1a) Using the matrix below, rank the listed sensors in order of importance (1 through 6) for immediate economic benefit to the user. Place these priority numbers in the row that corresponds to the application area(s) you are most familiar with.

	Touch*	Simple Force	Complex Force	Proximity	Simple Vision	Complex Vision
Spot Welding	2 (2.2)	4 (3.2)	5 (4.8)	3 (2.9)	1 (1.1)	6 (5.2)
Arc Welding	4 (3.7)	3 (3.1)	4 (3.7)	2 (2.5)	1 (1.2)	6 (4.6)
Aerospace laminate handling	2 (3.0)	3 (3.9)	6 (4.9)	5 (4.3)	1 (1.1)	3 (3.9)
Aerospace drilling, routing fastening	3 (2.6)	1 (1.6)	5 (4.3)	4 (4.2)	2 (2.4)	6 (5.2)
Small Part Assembly	1 (1.9)	3 (3.2)	5 (3.8)	6 (4.9)	2 (2.3)	4 (3.3)
Machine Tool loading/unloading	1 (1.2)	2 (2.4)	5 (4.6)	3 (2.7)	4 (3.6)	6 (5.4)
Press loading/unloading	1 (1.0)	2 (2.4)	5 (4.5)	3 (2.6)	4 (3.6)	6 (5.7)
Injection/Casting unloading	1 (1.1)	2 (2.4)	5 (5.0)	3 (2.6)	4 (3.8)	6 (5.4)

\*touch - presence or absence of parts

simple force - measure force along a single axis

complex force - measure force along two or more axes

proximity - non contact detection of part

simple vision - detect edges, holes, corners, etc.

complex vision - recognize shapes

Comments on 1a)

In completing the questionnaires the second time, the participants were instructed to provide comments for those responses that differed significantly from the average values in the first round. Several comments were received in the application area of small part assembly.

One person had ranked complex force as highest priority writing "complex force for aiding the teaching of an assembly system and monitoring its operation remains an unexploited economic capability."

Three of the participants had ranked complex vision as the highest priority in this area. Their comments were:

". . . without complex vision, very little small part assembly will ever be cost effective for robots because of part feeding."

". . . without complex vision for parts acquisition, I feel that the utility of an assembly robot in the work environment is seriously compromised."

. . . (complex vision is highest priority) "based on my view of aerospace applications without (or with minimum) tooling for acquisition and positioning."

#### Question 1b)

This question attempted to quantify to some degree the cost that a potential user felt he could justify for a particular sensor capability.

Originally, only those sensory capabilities that were ranked as the three highest priorities in question 1a) were to be cost justified here. However, for completeness, it was decided during the general discussion, to provide a cost figure for each of the six sensors.

#### Response to 1b)

- 1b) For the top three ranked sensors from question 1a, enter the cost that can be justified for the increased performance the sensor gives the robot system.

Ranking of Sensor Capability from 1a	Cost Justified per Robot (Thousand dollars)
1 Touch	2.0 (1.0 - 2.0)
2 Simple Vision	7.2 (5.0 - 8.0)
3 Simple Force	2.9 (2.0 - 3.0)
4 Proximity	2.7 (2.0 - 2.5)
5 Complex Force	3.2 (2.5 - 4.0)
6 Complex Vision	16.0 (10.0 - 15.0)

Question 1c)

This question addressed a different time frame than 1a). In question 1a), the participants were to prioritize sensory capabilities in terms of immediate, short-term economic benefit in their applications. Here, they are being asked to set a priority for research on sensors. That is, on what sensor systems should the research institutes expend their money and resources to provide the highest long term benefit? The results are expressed in the same form as in question 1a) There is a strong consensus that simple vision is the most important area for research..

Response to 1c)

- 1c) Using the matrix below, rank the listed sensors in order of priority (1 through 6) for expenditure of research and development money. Again, only fill in the row(s) that corresponds to the area(s) you are familiar with.

	Touch*	Simple Force	Complex Force	Proximity	Simple Vision	Complex Vision
Spot Welding	2 (2.0)	4 (3.6)	6 (4.2)	3 (2.9)	1 (1.0)	5 (4.2)
Arc Welding	4 (3.8)	5 (4.0)	3 (3.4)	5 (4.0)	1 (1.0)	2 (2.9)
Aerospace laminate handling	2 (2.3)	3 (3.4)	6 (4.8)	4 (4.2)	1 (1.2)	4 (4.2)
Aerospace drilling, routing fastening	4 (4.1)	2 (2.4)	6 (4.8)	4 (4.4)	1 (1.1)	3 (3.1)
Small Part Assembly	5 (4.2)	4 (4.1)	3 (3.7)	6 (5.2)	1 (1.6)	2 (1.9)
Machine Tool loading/unloading	3 (3.4)	2 (2.8)	3 (3.4)	6 (4.7)	1 (1.9)	5 (4.1)
Press loading/unloading	4 (3.7)	3 (2.9)	6 (4.6)	2 (2.8)	1 (1.2)	5 (4.3)
Injection/Casting unloading	1 (1.2)	4 (3.7)	6 (5.0)	5 (4.2)	2 (2.2)	3 (3.5)

\*touch - presence or absence of parts

simple force - measure force along a single axis

complex force - measure force along two or more axes

proximity - non contact detection of part

simple vision - detect edges, holes, corners, etc.

complex vision - recognize shapes

### Comments on 1c)

Two comments were received in the area of small part assembly.

". . . The role of simple vision in assembly has not been defined in any quantitative way, i.e. in economic models that allow trade off with other simpler sensor systems. For part identification there is no question (of the value of simple vision). Everything else needs careful justification. With the present specs on location of parts - approximately 1" - then the use of a simple force vector steering system appears economically more interesting from reliability as well as performance compared to vision. Also no problem with the environment."

". . . In view of the CSD (Charles Stark Draper) labs remote center compliance unit, complex force seems unnecessary."

One comment was received in the areas of injection/casting unloading and press Loading/unloading with complex vision:

complex vision ". . . not necessary unless addressed to bin picking and a superior program . . . then top priority."

### Question 2)

The participants were asked to predict the year that each of the previously mentioned sensory capabilities would be commercially available to be used with robot systems. They also predicted the year that each sensory capability might be expected to be on 50% of the robots shipped.

### Response to 2)

- 2) For each of the sensors below, predict the year when robots will be commercially available with that capability and predict the year when 50% of the robots shipped will have that capability.

	Year Commercially Available	Year that Capability Available on 50% of Robots Shipped
Touch	1977 (1977 - 1978)	1983 (1980 - 1985)
Simple Force	1979 (1977 - 1980)	1986 (1982 - 1990)
Complex Force	1981 (1980 - 1982)	1988 (1987 - NEVER)
Proximity	1978 (1977 - 1979)	1986 (1985 - NEVER)
Simple Vision	1978 (1977 - 1979)	1990 (1985 - 2000)
Complex Vision	1983 (1982 - 1985)	1993 (1990 - NEVER)

Question 3)

This question was an attempt to quantify the amount of imprecision of the workpiece location that a robot would have to cope with. This was done by asking the participants to provide the percentage of their application area that was characterized by differing degrees of uncertainty in the position and orientation of the workpiece. Thus, a situation where the workpiece was always located exactly in the same position and orientation to within plus or minus .050 of an inch and plus or minus 1° would be classified as precise. At the other end of the range, a part whose position and orientation were not at all known, such as a part in a bin of parts, would be classified as random. The amount of this imprecision in position and orientation would to some extent determine the types of sensors required for the robot to locate and work with the parts.

Response to 3)

- 3) Enter the percentage of work in the application area(s) you are familiar with that is characterized by the degree of part misalignment described in each column of the matrix below. Within an application area (a row in the matrix), the percentages should sum to 100%.

	Ultra* Precise	Precise	Crude	Surface	Random
Spot Welding	14	58	26	2	
Arc Welding	12	62	23	3	
Aerospace lamine handling	35	47	8		
Aerospace drilling, routing fastening	62	35	3		
Small Part Assembly	30	47	15	6	2
Machine Tool loading/unloading	17	58	13	6	6
Press loading/unloading	14	58	13	6	6
Injection/Casting unloading	38	60	2		

\*ultra precise - locate part where position known to <.050"  
 precise - locate parts where position is known with ±.050", ±1°  
 crude - locate parts where position is known within ±1", ±20°  
 surface - locate parts on a known surface but with random orientation and position  
 (e.g. part randomly oriented on a conveyor)  
 random - locate parts with large displacements in all three positional coordinates  
 and all three rotational coordinates (e.g. bin picking)

Question 4)

In some applications, the workpieces are on a continuous moving transfer or conveyor system and work must be done on these parts while in motion. This question was meant to quantify the amount of work in each application area characterized by the need for the robot to track a moving line.

Response to 4)

- 4) What percentage of the tasks in the application area(s) you are familiar with require the robot to be able to track a moving line.

Percentage of  
Application Area  
Requiring Line Following

Spot Welding	51
Arc Welding	7
Aerospace laminate handling	1
Aerospace drilling, routing fastening	0
Small Part Assembly	30
Machine Tool loading/unloading	13
Press loading/unloading	6
Injection/Casting unloading	0

Question 5)

This question pertains only to those applications where the robot is tracking a moving line. The participants were asked to quantify the amount of imprecision in this environment by providing the percentages of their line following applications that were characterized by the different classes of uncertainty as in question 3.

Response to 5

- 5) Enter the percentage of the line following work in your application area(s) that is characterized by the degree of part misalignment described in each column of the matrix below. Within an application area (a row in the matrix), the percentages should sum to 100%.

	Ultra* Precise	Precise	Crude	Surface	Random
Spot Welding	6	41	48	4	1
Arc Welding	2	42	54	2	
Aerospace laminate handling	25	75			
Aerospace drilling, routing fastening					
Small Part Assembly	9	44	32	13	2
Machine Tool loading/unloading	13	33	44	10	
Press loading/unloading	2	26	37	35	
Injection/Casting unloading					

\*ultra precise - locate part where position known to <.050"  
precise - locate parts where position is known within  $\pm .050"$ ,  $\pm 1^{\circ}$

crude - locate parts where position is known within  $\pm 1"$ ,  $\pm 20^{\circ}$

surface - locate parts on a known surface but with random orientation and position  
(e.g. part randomly oriented on a conveyer)

random - locate parts with large displacements in all three positional coordinates  
and all three rotational coordinates (e.g. bin picking)

C. CONTROL

Question 6)

Robots can be equipped with varying degrees of control capability. These different levels of control are characterized by differences in time and ease of programming, in flexibility, in ability to move along straight lines in the ability to interact with sensory data etc. Five different levels of control were listed. The participants were asked to estimate the percentages of robots shipped in 1980, 1985, and 1990 that would have these different control capabilities.

Response to 6)

- 6) Estimate for each of the years given below the percentage of robots shipped that will have the control capabilities listed. Each column should sum to 100%.

	1980	1985	1990
Point-to-Point adjustable stops	28% (25-30)	21% (20-25)	16% (15-20)
Servo Point-to-Point teach mode	39% (30-50)	32% (25-40)	23% (15-30)
Continuous Path	13% (10-15)	14% (10-15)	15% (10-20)
Coordinate Transformation (straight line, joystick, line following)	15% (10-20)	21% (15-25)	23% (15-25)
Sensor Integration and Higher Levels	5% (5-5)	12% (10-15)	23% (20-30)

Question 7)

In this question, 5 different teach/program methods were listed. These methods represent a large range of programming capability from a simple rate control box to automatic program generation by high level computer strategies.

The participants were asked to estimate the year each of these methods would be commercially available and the year by which 50% of the robots shipped would be characterized by that teach/program method.

Response to 7)

- 7) For each of the teach/program methods listed in the matrix below, estimate the year when first commercially available and the year when 50% of the robot shipments will be characterized by that method.

	Year Commercially Available	Year 50% of Shipments Use this Method
Teach-Playback (rate control box)	Now	Now
Teach-Playback in external coordinates (joystick; x,y,z push- buttons etc.)	Now	1982 (1980-1984)
Teach-Playback with editing	Now	1984 (1982-1985)
Off-Line Programming/ Higher Level Languages	1982 (1980-1985)	1992 (1987-2000)
Automatic Programming (computer generates robot program)	1986 (1985-1987)	1996 (1995-NEVER)

Comments on 7)

One comment was received with regards to the off-line programming/higher level languages capability:

". . . 50% of all robots shipped will not in the foreseeable future use off-line programming - not cost-effective."

Question 8)

This question attempted to quantify the percentage of applications for robots integrated into a system rather than as stand alone units. The main distinguishing feature of this type of integration would be the presence of some kind of control at least one level higher than the robot itself which would coordinate the robot's program(s) with the requirements of a total system.

Response to 8)

- 8) For the years listed below, estimate the percentage of robots that will be incorporated into integrated computer-aided manufacturing (ICAM) systems.

	1980	1985	1990
Percentage of Robots in Integrated Systems	4% (2-5)	10% (5-10)	17% (10-20)

Question 9)

This question was concerned with determining some of the performance requirements necessary for the robot to be used effectively in the different application areas. This would allow the users to emphasize their needs as they see them in order to be able to use industrial robots. Six general performance characteristics relating to robot control were listed here. The participants assigned a number indicating relative importance to each of these characteristics. The numbers ranged from a value of one, indicating that this characteristic was critical to the successful implementation of the robot, to a value five, indicating that this capability would never be needed.

During the general discussion period, a quantitative value of .010 inch to .050 inch was assigned to the performance characteristic of high positional accuracy.

Response to 9)

9) For each of the performance characteristics described in the columns below, enter a number from 1 to 5\* to indicate its importance to the application area(s) you are familiar with.

	Fast Short Moves	High Slewing Speeds	High Positional Accuracy	Sensor Directed Control	Fast Programming	Off-Line Programming
Spot Welding	1.2	2.3	1.7	2.7	3.0	4.0
Arc Welding	4.2	3.5	1.2	1.9	2.7	3.2
Aerospace laminate handling	3.3	2.6	1.0	1.3	1.9	1.7
Aerospace drilling, routing fastening	1.9	2.2	1.2	2.0	2.0	2.1
Small Part Assembly	1.1	1.4	1.2	1.8	2.4	2.9
Machine Tool loading/unloading	2.4	2.1	1.7	2.7	2.6	3.0
Press loading/unloading	1.9	1.4	1.9	3.0	3.1	4.1
Injection/Casting unloading	2.0	1.3	1.7	3.6	3.4	4.3

\*1 - critical to the application

2 - highly advantageous for more effective and efficient use of robot

3 - offers some advantages but not absolutely necessary

4 - may need this capability sometime

5 - never need this capability

Comments on 9)

One comment was received on the results of the first round (which were not significantly different from this second round reported here)

"... seeing the bland consensus, I would suspect that few really know what is needed because there is no depth of experience of actually trying the jobs and economically justifying the robot."

D. MARKET

Question 10)

The participants of the workshop were asked to predict the number of robots that would be shipped and the dollar value of these shipments for the years 1980, 1985 and 1990.

During the general discussion, it was decided that this figure should apply to the United States only, not world wide projections.

Response to 10)

- 10) Estimate the number of robots shipped and the dollar value of these shipments for each of the years listed.

	1980	1985	1990
Number of Robot Units Shipped (in thousands)	1.3 (1.0-1.5)	3.3 (2.2-5.0)	12.2 (5.0-20.0)
Dollar Value of Shipments (in million dollars)	68 (50-100)	214 (120-300)	700 (250-1000)

Comments on 10)

Two comments were received with the responses:

"... All estimates of how fast robots are coming in the past have been far too high and I believe they still are. It's primarily a question of economics and the economics of robots are not changing fast enough to justify such large growth predictions."

The other comment considered the validity of making this projection for just the United States market since at least one robot manufacture exports a large percentage (40%) of his product. This answer was given relative to the world wide market. These dollar value figures were 1980 - \$300M, 1985 - \$900M, 1990 -\$3000M.

E. SUMMARY

Certain general conclusions drawn from the preceding data will be presented here by way of a summary of the Delphi forecast.

Sensor controlled movements of robots appear to be a highly desirable feature in the implementation of robots in present and future applications. The most desirable sensory capabilities are simple vision in welding and aerospace laminate handling applications and touch in assembly, machine tool, press and casting operations.

The robot users feel that a cost of \$7000 can be justified for simple vision and \$2000 for touch sensing.

There was a strong consensus among all participants that simple vision is the number one priority for research and development efforts.

All sensory capabilities including complex vision are seen to reach commercial availability before 1985.

The data supplied here indicates that for almost all applications, the workpiece's position and orientation are already known to within plus or minus 1" and plus or minus 20 degrees. This type of imprecision in the known location of the workpiece should be easily accommodated for by simple vision.

Those problems requiring complex vision are characterized by a greater uncertainty in the environment and are typified by the acquiring of parts from a bin. These are mainly the areas of machine tool and press loading.

Most of the line following work is in the spot welding and assembly areas, with some of the machine and press loading being done with parts from moving conveyors.

With the moving line work, the position and orientation of most parts is known to within plus or minus 1" and plus or minus 20 degrees. This emphasizes the ability of a simple vision system to accommodate a large number of applications.

A shift was seen into the middle and late 1980's away from the simple bang-bang, and point-to-point servo control systems to more sophisticated computer control that would perform coordinate transformations and sensory feedback control.

By 1985 it was felt that 10% of the robots would be incorporated to integrated computer-aided systems.

The advance in both control and sensory capability will be strongly driven by the continuing decreasing costs of computers which will also spur the development of the integrated systems.

The performance characteristics judged most critical to the different application areas are summarized here. In spot welding, high speed for both short and long distance moves and high positional accuracy are required. Arc welding needs high positional accuracy and sensor control. Aerospace work and small part assembly are complex tasks heavily dependent on all performance characteristics. The machine tool, press, and casting operations need high speed movement for both short and long distances and high positional accuracy.

Finally, the market projections for robots in the United States show about a 25% growth per year from 1980 to 1990 with a market prediction of around \$200 million in 1985. The average price per robot is estimated at \$52,000 in 1980, \$65,000 in 1985 and \$57,000 in 1990.

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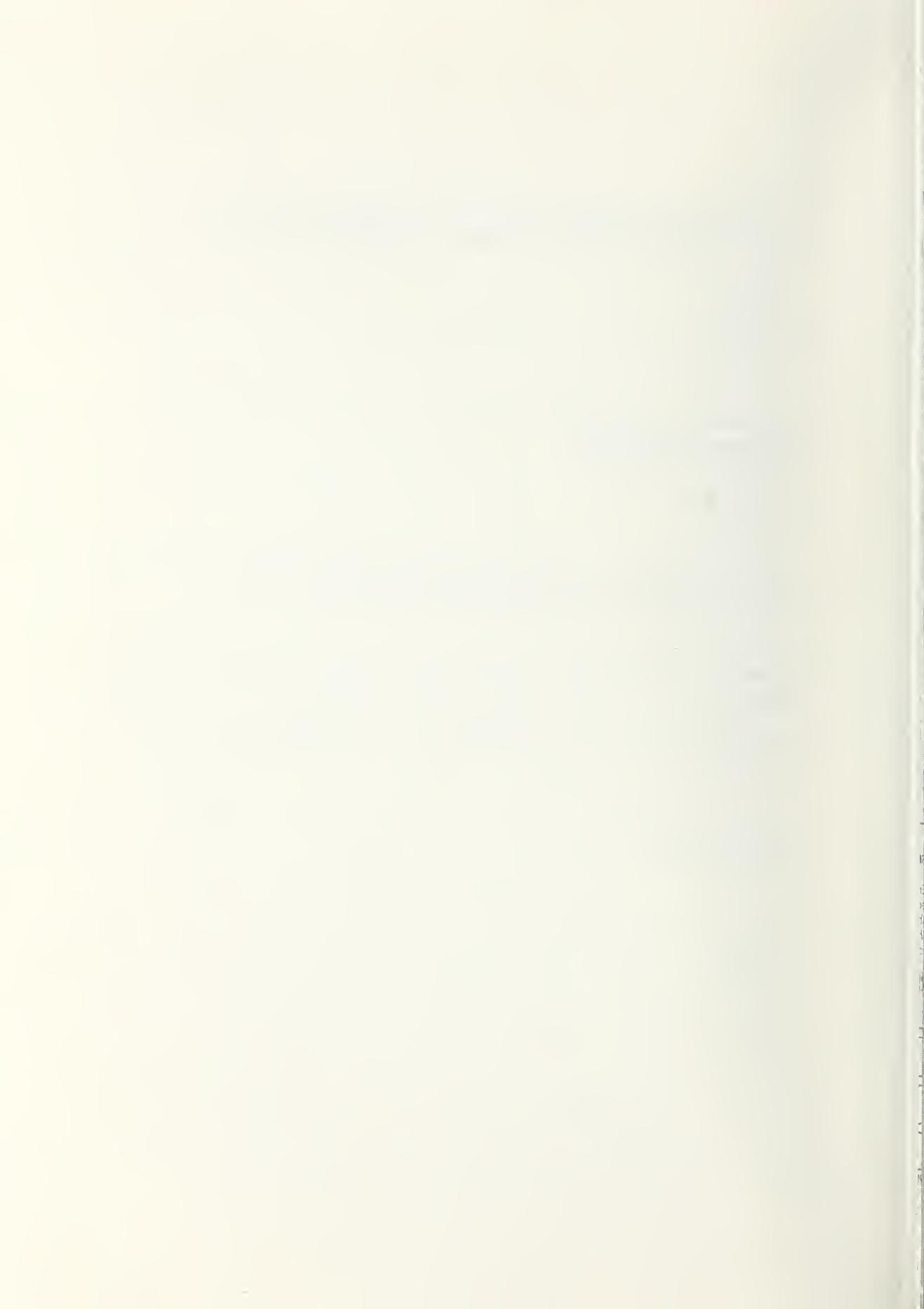
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